

LOW-MASS X-RAY BINARIES AND GLOBULAR CLUSTERS IN CENTAURUS A¹

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ABSTRACT

We present results of *Hubble Space Telescope* and *Chandra X-ray Observatory* observations of globular clusters (GCs) and low-mass X-ray binaries (LMXBs) in the central regions of Centaurus A. Out of 440 GC candidates we find that 41 host X-ray point sources that are most likely LMXBs. We fit King models to our GC candidates in order to measure their structural parameters. We find that GCs that host LMXBs are denser and more compact, and have higher encounter rates and concentrations than the GC population as a whole. We show that the higher concentrations and masses are a consequence of the dependence of LMXB incidence on central density and size plus the general trend for denser GCs to have higher masses and concentrations. We conclude that neither concentration nor mass are fundamental variables in determining the presence of LMXBs in GCs, and that the more fundamental parameters relate to central density and size.

Subject headings: galaxies: elliptical and lenticular, cD — globular clusters: general — X-rays: binaries

1. INTRODUCTION

Since the discovery of X-ray sources associated with globular clusters (GCs) in the Milky Way (MW; e.g., Giacconi et al. 1974) it has been known that low-mass X-ray binaries (LMXBs) are formed more efficiently in GCs by a factor of 100 compared to the field (Katz 1975; Clark 1975). This is thought to be a direct consequence of the high central densities in GCs. At high density, dynamical formation mechanisms are greatly enhanced relative to the field (Clark 1975; Fabian et al. 1975; Hills 1976).

While the dynamical origin of most GC LMXBs was proposed three decades ago, subsequent observational studies of the core properties of GCs that host LMXBs have been largely restricted to the MW. The *Chandra X-ray Observatory* has made it possible to study the LMXB populations of nearby ($\lesssim 30$ Mpc) galaxies (e.g., Fabbiano 2006 and refer-

ences therein), but the core properties of the GCs, which are thought to be the most relevant in the dynamical processes that create LMXB progenitors, are not robustly determined even with *HST* for most of those galaxies.

In the MW, Bellazzini et al. (1995) showed that bright LMXBs appear in denser and more metal-rich GCs, while Pooley et al. (2003) and Heinke et al. (2003) showed that the number of GC X-ray sources correlates with Γ , a basic indicator of dynamical encounter rates defined as $\Gamma \equiv \rho_0^{1.5} r_c^2$ (e.g., Verbunt et al. 2007), where ρ_0 is the central mass density and r_c is the core radius. Bregman et al. (2006) showed additionally that bright GC LMXBs in the MW appear preferentially in GCs with smaller core and half-light radii and shorter half-mass relaxation times. Sivakoff et al. (2007; S07) used 11 early-type galaxies to show that encounter rates are a good predictor for the appearance of LMXBs in GCs, deriving Γ from measurements at the half-light radii. This is consistent with earlier results in M87 that used more uncertain derived core properties (Jordán et al. 2004; J04).

To make further progress in understanding the dynamical processes that create LMXB progenitors in the cores of GCs it is necessary to directly observe LMXBs and the core structure of the GCs that host them for as large a sample as possible. In this work, we use *HST/ACS* and *Chandra* observations of the central regions of Centaurus A (or NGC 5128; hereafter Cen A) in order to extend such studies beyond the Local Group. At the distance of Cen A, $D \approx 3.7$ Mpc (average of 5 distance indicators, see §6 in Ferrarese et al 2007), it is possible to study the central properties of GCs with *HST*, an ability we exploit in what follows in order to study which structural properties of GCs are most relevant in determining the presence of LMXBs in GCs.

2. OBSERVATIONS

Optical Catalog. We have made use of 21 fields in Cen A observed with the F606W filter using the Wide Field Channel mode of the *Advanced Camera for Surveys* (ACS) on board the *Hubble Space telescope* (HST). Nine of these fields were observed as part of program GO-10597 (PI: A. Jordán), which

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was designed to be combined with previous observations from program GO-10260 (PI: W.E. Harris) in order to cover a large area in the inner $r \lesssim 8$ kpc plus some fields at larger radii.

Each field of GO-10597 consists of four 525-sec exposures plus a single 58-sec exposure, while the data of GO-10260 consist of three exposures of 790 sec. Full observational details of GO-10260 are given in Harris et al. (2006), but we note that for this study we have re-reduced the GO-10260 data in parallel with our reductions of the new GO-10597 data to construct an independent and homogeneous catalog of GCs. A detailed account of the data reduction procedures and GC catalog construction will be given elsewhere so only a brief summary follows here.

All data were drizzled using the Apsis package (Blakeslee et al. 2003) onto frames with a pixel scale of $0''.05$. Object detection and photometry were performed using SExtractor (Bertin & Arnouts 1996). Our detection threshold corresponds to $m_{F606W} \sim 22$ AB mag and is such that we are not subject to incompleteness effects. We used photometric zeropoints and extinction coefficients from Sirianni et al. (2005) and de-reddened the photometry using $E(B-V) = 0.115$ (Schlegel et al. 1998). We dealt with foreground-star contamination by eliminating all objects that were consistent with the point-spread function (PSF). We matched our object catalog with the full photometric catalog (56,674 objects) of Peng et al. (2004), obtaining *VI* photometry for all objects for which a match was found. The same catalog was used to place our objects on a consistent astrometric frame. For objects which did not have a match in Peng et al., we further matched to deep *VI* photometry of the central regions of Cen A obtained with the VLT (Minniti et al. 2004).

An azimuthally averaged surface-brightness profile was obtained for each object using the ELLIPSE task in IRAF. We then fit PSF-convolved King (1966) models to each object following the procedures applied by McLaughlin et al. (2007) to the GO-10260 data (see also Barmby et al. 2007). The best-fit models were used to infer various global and core parameters for every GC.¹⁴

To infer mass-based cluster quantities we used *F606W* mass-to-light ratios as a function of $(V-I)$ color derived from the models of Bruzual & Charlot (2003) assuming an age of 13 Gyr for all objects¹⁵. We culled our catalog by rejecting objects with $(V-I) < 0.6$, $(V-I) > 1.55$ or concentration $c > 2.5$. We further eliminated objects whose surface-brightness profiles spanned less than 0.5 mag arcsec⁻² or that were visually deemed to be background objects. The final catalog consists of 440 objects, 407 of which have *VI* photometry available. We estimate that $\sim 3\%$ of these objects may be contaminating background galaxies (based on an analysis of 21 control fields observed in the same filter to similar depths, and analyzed in the same fashion as our Cen A program fields).

X-ray Catalog. Prior to 2007, *Chandra* observed Cen A with the ACIS detectors four times (Observations 316, 962, 2978, and 3965). In 2007, *Chandra* performed six deep observations (~ 100 ks each) of Cen A as part of the Cen A

Very Large Project (CenA-VLP; PI: R. Kraft). In this analysis, we report initial results from an X-ray point source list constructed using the first four CenA-VLP observations (Observations 7797, 7798, 7799, and 7800) plus the previous observations listed above.

The reduction of the *Chandra* data prior to 2007 is described in Woodley et al. (2007). The reduction of the CenA-VLP observations (a total of 373,353 s) will be presented in detail in forthcoming papers; here, we only consider a few aspects relevant to point source detection (see Hardcastle et al. 2007 for an image of the X-ray data). Sources were detected in the 0.5–7 keV X-ray image from each observation using WAVDETECT with wavelet scales spaced by a factor of $\sqrt{2}$ and ranging from 1 to 32 pixels, with a source detection threshold of 10^{-7} . Sources that were not associated with the X-ray jet or lobes in Cen A were used to register the relative astrometry between the observations. The majority of the detected sources are X-ray binaries in Cen A, and in particular the ones associated with GCs are expected to be LMXBs. In what follows we will use the term LMXBs for X-ray sources associated with GCs.

Source Matching. After determining the astrometric offsets required to bring the astrometry of our list of X-ray sources into the same system as the GCs, we carried out source matching with a matching radius of $1''.6$, obtaining 41 matches. With our chosen matching radius we expect $\lesssim 1$ false matches. The *rms* difference between the X-ray and optical positions for matched sources was $\lesssim 0''.5$ in both right ascension and declination.

3. RESULTS

Previous studies have found that LMXBs appear preferentially in more luminous (massive) and redder (metal-rich) GCs (e.g. S07; Kundu et al. 2007; see Fabbiano 2006 for a recent review and Minniti et al. 2004 and Woodley et al. 2007 for studies in Cen A). Metal-rich GCs are ≈ 3 times more likely to host a LMXB, although the scatter around this value for different galaxies is significant.

In the leftmost panel of Figure 1 we show the histogram of AB magnitude in the *F606W* band for all GC candidates (unfilled histogram) and for those that have an associated X-ray point source (filled histogram). The next panel shows equivalent histograms in $(V-I)$ color for sources with *VI* photometry. The numbers in each of the panels of this figure show the *p*-value of a two-sample Wilcoxon test between the two distributions shown. The *p*-value gives the probability that the two distributions have the same mean values. It is clear that there is a strong preference for LMXBs to be hosted by more luminous (massive) GCs. The color distribution of LMXB hosting GCs is slightly more weighted toward redder GCs, although the difference between the mean of the two distributions is not significant for our sample.

In the five rightmost panels of Figure 1 we show histograms of central mass density (ρ_0), core encounter rate (Γ), King (1966) core (r_c) and half-light (r_h) radii and concentration $c \equiv \log(r_t/r_c)$, where r_t is the model tidal-radius, for all GCs (unfilled histograms) and those that host an X-ray point source (filled histograms). In agreement with observations in elliptical galaxies (J04; S07) and the MW (Bregman et al. 2006), we find that the GCs hosting LMXBs have smaller half-light radii and higher encounter rates. Our new observations allow us to show explicitly for the first time in an elliptical galaxy that they also have significantly smaller core radii and higher central densities, as is the case in the MW (Bellazzini et al.

¹⁴ At the distance of Cen A, a typical GC core radius of $r_c \sim 1$ pc corresponds to $0''.056$, comparable to the half-width at half-maximum of the PSF. Holland, Côté, & Hesser (1999) and Harris et al. (2002) have shown that estimates of r_c from PSF-convolved King-model fitting in this situation are unbiased in general, and Barmby et al. (2007) have shown that the fits of McLaughlin et al. (2007) to the GO-10260 GCs in Cen A, which include $\sim 25\%$ of the GCs in our sample, give rise to core-parameter correlations that are consistent with those found for MW GCs.

¹⁵ For objects without measured $(V-I)$ we used $(M/L)_{F606W} = 2.2$ in solar units.

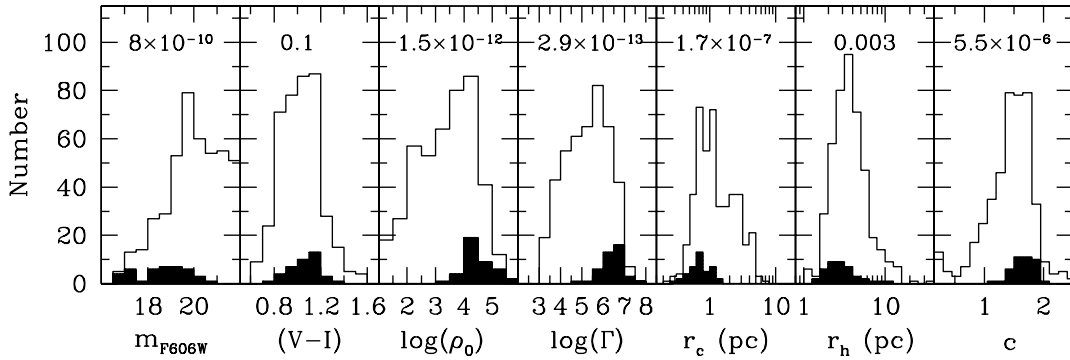


FIG. 1.— This figure shows histograms of total apparent F606W AB magnitude (m_{F606W}), de-reddened $(V-I)$ color, logarithm of the central mass density (ρ_0 , in units of $M_\odot \text{ pc}^{-3}$) and encounter rate ($\Gamma \equiv \rho_0^{1.5} r_c^2$), King (1966) core radii (r_c), half-light (r_h) radii and concentration (c) for the full sample of GCs (unfilled histograms) and for the subsample that coincide with an X-ray source (filled histograms). The numbers in each of the panels of this figure show the p -value of a two-sample Wilcoxon test between the two distributions shown. The p -value gives the probability that the two distributions have the same mean values.

1995; Bregman et al. 2006). Finally, the concentration is also found to be higher in LMXB-hosting GCs (but see below).

It is well known that many of the structural properties of GCs in the MW are correlated with one another (e.g., see Djorgovski & Meylan 1994; McLaughlin 2000). It is therefore important to ask which of the parameters in Figure 1 might be fundamental in determining the presence or absence of LMXBs in GCs, and which parameters might just appear to be important because they correlate with more physically relevant properties. Of particular interest is disentangling the degeneracy between central density (and, thus, the encounter rate $\Gamma \equiv \rho_0^{1.5} r_c^2$) and total mass, which arises from the fact that massive GCs are denser on average (McLaughlin 2000; Jordán et al. 2005). In principle, other quantities of relevance to LMXB production—such as, e.g., the fraction of primordial binaries—might depend on GC mass but not on either of ρ_0 or Γ on its own, which leaves the implications of Figure 1 somewhat unclear.

We may empirically probe which GC properties influence the presence of LMXBs in GCs *after taking into account any dependences on total mass*, by comparing the properties of clusters that host LMXBs with the properties of clusters that do not host LMXBs but have the same underlying mass distribution. To do this, we first estimate the mean dependence of each of $Y = \{\rho_0, \Gamma, r_c, r_h, c\}$ on GC mass M for GCs that do not host an LMXB using a robust local smoothing of the M - Y scatterplot performed with the Lowess method (Cleveland 1979). We then use the functions $\hat{Y}(M)$ thus estimated to predict the expected average of the variable Y when having the same mass distribution as the GCs that host LMXBs by computing $\langle Y \rangle = N^{-1} \sum_{i=1}^N \hat{Y}(M_i)$, where M_i are the masses of the $N = 41$ GCs that host LMXBs.

We show the result of this exercise in Figure 2, where we show various distributions of structural quantities for GCs that host LMXBs, indicating with an error bar the 99% confidence interval for the median of these distributions and with an arrow the expected median for GCs that do not host an LMXB and have the same underlying mass distribution. The result of a one-sample Wilcoxon test to estimate the probability that the median of the LMXB-hosting sample is consistent with that expected for GCs that do not host LMXBs is indicated in each panel.

A very interesting result is given by the rightmost panel in Figure 2: after the effects of mass are taken into account, the

average King concentration shows no statistical difference between GCs that host LMXBs and those that do not. In the MW there is a trend for more massive GCs to be more concentrated, roughly following $10^c \propto M^{0.4}$ (McLaughlin 2000). A consistent trend is also present in our sample. We have shown that once this trend is taken into account *concentration per se has no significant effect in determining the presence of LMXBs*.

Figure 2 also shows that all of ρ_0 , Γ , r_c , and r_h have mean values that are significantly different for GCs that host LMXBs, *even when considering clusters with the same mass distribution*. Thus, processes driven by high core densities, and presumably related to high stellar encounter rates, play a direct role in enhancing the presence of LMXBs in GCs; the dependences on core properties and r_h in Figure 1 are not purely coincidental side effects of physics or initial conditions that scale fundamentally with cluster mass only.

Is there a role left for GC mass in determining the presence of an LMXB after the dependence on ρ_0 and r_c (through Γ) has been taken into account? We can answer this question by repeating the exercise above but now comparing the mass distribution of GCs that host LMXBs with those of GCs that do not host LMXBs and have the same underlying distribution of Γ . We find when doing this that the average mass of GCs that host LMXBs is statistically indistinguishable to that of GCs that do not (Wilcoxon p -value of 0.98). As there are no remaining differences in the average masses after dependencies in structural parameters have been taken into account through Γ , we conclude that *the dependence of LMXB incidence on mass is a consequence of a more fundamental dependence on central density and size*. We note also that c shows no significant difference between GCs that host LMXBs and those that do not when considering the same underlying Γ distributions.

We follow the procedure described in §4 of S07 to determine the dependence of the expected number of LMXBs, λ_t , on GC properties using a maximum-likelihood method. In particular, we fit for the exponents in the following assumed forms for λ_t : (1) $\lambda_t \propto M^\beta 10^{\delta(V-I)} r_h^\epsilon$ and (2) $\lambda_t \propto \Gamma^\eta 10^{\delta(V-I)}$.

We find that the values of δ obtained are not significantly different from zero. This is consistent with the fact that the $(V-I)$ color distribution of GCs that host LMXBs is not significantly different from the global color distribution in our sample. When using the functional form (1) we find $\beta = 1.4 \pm 0.2$, $\delta = 0 \pm 0.6$ and $\epsilon = -2.1 \pm 0.4$, while using form

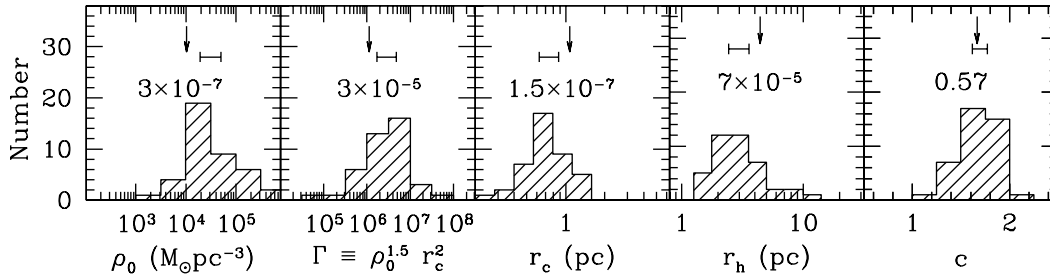


FIG. 2.— This figure shows histograms of the central mass density (ρ_0), encounter rate ($\Gamma \equiv \rho_0^{1.5} r_c^2$, King (1966) core radii (r_c), half-light (r_h) radii and concentration (c) for the full the sample of GCs that are associated with an X-ray point source (X-GCs). The error bar in each panel shows a 99% confidence interval for the median of each distribution and the arrow indicates an estimate of the expected value of that median for GCs that do not hold LMXBs (nX-GCs) and that have the same underlying mass distribution as the GCs shown in the histogram. The number in each panel is the p -value of a one-sample Wilcoxon test to test the probability that the sample median is consistent with the value indicated by the arrow. The ratio of the median values of the quantities that show significantly different distributions (in the sense X/nX) are: 2.1 (ρ_0), 1.93 (Γ), 0.68 (r_c) and 0.77 (r_h).

(2) we find $\delta = -0.3 \pm 0.6$ and $\eta = 0.85 \pm 0.12$. These results are in good agreement with the results of S07 for Virgo Cluster ellipticals, where the analysis was restricted to using quantities defined at the half-mass radius.

4. CONCLUSIONS

We have shown in this *Letter* that GCs in Cen A that host LMXBs have significantly higher central densities, smaller sizes, and higher concentrations than the GC population as a whole. The higher concentrations are shown to result from the dependence of LMXB incidence on central density and size, plus the fact that denser (or more massive) GCs are more centrally concentrated on average.

More importantly, we have used our Cen A sample to compare the properties of LMXB-hosting GCs to those that do not but have the same underlying mass or Γ distribution. We find that GCs that have LMXBs have significantly higher central densities, encounter rates and smaller sizes than GCs of the same mass that do not have LMXBs. Interestingly, we find that the mean concentrations are indistinguishable once the trend for more massive GCs to have higher concentrations is removed. As r_h/r_t depends only on c for King models, our conclusion agrees with the MW data presented in Bregman et al. (2006; their Figure 1).

We further show that potential GC mass-dependent processes are not fundamental in the formation of GC LMXBs

(see also S07; Verbunt et al. 2007). It is rather smaller sizes and denser cores, or equivalently higher values of the core encounter rate Γ , that are the main drivers.

Finally, our finding that concentration is not important in determining the presence of LMXBs in GCs validates the use of half-mass densities and radii to probe the dynamical properties of GCs and their connection to the presence of LMXBs. This is helpful as core properties are uncertain for GCs in galaxies much more distant than Cen A. The detailed dependence of LMXB incidence on GC core properties will aid in further understanding of the interplay of various dynamical processes in creating X-ray binaries (e.g., Banerjee & Ghosh 2006; Ivanova et al. 2007). In particular, we find in agreement with previous work (J04; S07) that the dependence of the expected number of LMXBs λ_t on encounter rate, $\lambda_t \propto \Gamma^{0.85}$, is shallower than the naively expected linear behavior.

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